Developing a wheat precision nitrogen management strategy by combining satellite remote sensing data and WheatGrow model

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Abstract.

Precision nitrogen (N) management is becoming increasingly popular due to its ability to synchronize crop N demand with soil N supply spatiotemporally. Crop growth model serves as an effective tool to explore optimal crop management strategies, yet the potential of the WheatGrow model in this regard remains unclear. The objectives of this study were (1) to calibrate and evaluate the WheatGrow model using field wheat experiments and peer-reviewed papers in Jiangsu Province; (2) to evaluate an in-season N management strategy based on WheatGrow model in comparison with farmers conventional N rates and N rates corresponding to attainable yield (Natt). Data from N plot experiments and peer-reviewed papers were equally divided for calibration and evaluation purposes. Overall, the model provided accurate estimations of growing stages and grain yield across N rates for both calibration (RMSE= 3.1-10.2 days and 643-1266 kg/ha) and evaluation (RMSE= 4-10 days and 776.8-1598 kg/ha), respectively. The calibrated model was utilized to determine the in-season economic optimal N rate (EONR) by integrating current and five years of historical weather data. Approximately 100% of predicted EONR values fell within 20% of agronomic optimal N rates. In-season EONR demonstrated the potential to reduce N rates by 30%-36% and improve Partial Factor Productivity (PFP) by 33%-51% without *compromising grain yield, compared with current farmer practices and Natt, respectively. The results of this work lays the foundation to develop methods for making N decisions using crop growth model in this area.*

Keywords.
WheatGrow model, wheat yield, in-season nitrogen strategy, economic benefits

Introduction

Wheat is one of the world's three major food crops, contributing 40% to the global food supply, and holds a crucial role in global food production (FAO,018). China is the largest producer and consumer of wheat, with widespread cultivation across the country, making it a vital grain reserve species (Liu et al., 216). In practice, the high cost associated with under-fertilization compared to over-fertilization drives farmers to apply nitrogen (N) at higher rates as a safeguard against yield losses (Moebius-Clune et al., 2013). Therefore, effective N fertilizer management is essential for both economic and environmental reasons (Scharf 2015). Optimal N management requires farmers to make informed decisions regarding the form, timing, placement, and rate of N fertilizer application. Precision N Management offers a promising approach to achieving high crop yields and environmental benefits by synchronizing soil N supply with crop N demand in both space and time (Cao et al., 2016).

The WheatGrow model (v3.0) is a process-oriented mechanism model used to investigate spatial yield variations and evaluate the economic benefits of transitioning from uniform to variable rate management. It comprises five submodules: apical development and phenological development (Yan et al., 2000), photosynthesis and biomass production (Liu et al., 2003), dry matter partitioning and organ establishment (Liu et al., 2001), yield and quality formation (Pan et al., 2006; Pan et al., 2007), and soil water and nutrient balance (Hu et al., 2004; Yang, 2004). Inputs for the WheatGrow model include variety parameters, meteorological data, soil physical properties, and management practices. Research has shown that the WheatGrow model effectively evaluates yield potentials under different climate scenarios (Ye et al., 2021) and simulates rice growth dynamics under extreme low temperatures (Kang et al., 2022). However, the model has not yet been assessed for N fertilizer optimization in the wheat systems of Jiangsu Province, China. This study aims to calibrate and evaluate the WheatGrow model using field experiments and published literature in Jiangsu Province, and to assess an in-season N management strategy compared to farmers conventional N rates (FCN) and N rates corresponding to attainable yield (Natt).

Materials and Methods

Study area and design

This study was conducted in Jiangsu Province, eastern China. Experiment 1 (2015–2016) was carried out at Sihong Experimental Station (33.37°N, 118.26°E) using the wheat variety "Huaimai20," grown at five nitrogen (N) levels: 0, 90, 180, 270, and 360 kg N ha^{-1}. Sihong Experimental Station is situated in a warm temperate monsoon climate zone, receiving approximately 2300 hours of sunshine and 910 mm of annual rainfall, with an average temperature of 16.2°C. Experiment 2 (2017–2020) was conducted at Xinghua Experimental Station (33.08°N, 119.98°E) using the wheat variety "Yangmai23," also grown at five N levels: 0, 90, 180, 270, and 360 kg N ha−1. Xinghua Experimental Station is located in a subtropical monsoon climate zone, with around 2120 hours of sunshine, 900 mm of annual rainfall, and an average temperature of 17.3°C. Plants were spaced 25 cm apart and grown at a density of 2.25 million seedlings per hectare. A randomized complete block design with three replicates was used for each treatment. Plot sizes were 42 m² (6 m × 7 m) in Experiment 1 and 63 m² (7 m × 9 m) in Experiment 2. The varieties were sown manually in each plot. Granular urea was used as the N fertilizer in all experiments, applied in two stages: 50% before sowing and 50% at the wheat jointing stage. Based on soil analysis results and recommendations from the local agricultural department, 105 kg P2O5 ha−1 was applied before sowing in the form of Ca(H2PO4)2, and 135 kg K2O ha−1 was applied in two splits: 50% before sowing and 50% at the stem elongation stage. Irrigation was applied one time to ensure the seeds germinated securely after sowing if there was no rainfall.

In addition to field experiments, data for this study were obtained from peer-reviewed published papers. The keyword "Zhenmai12" was used to search the Web of Science. The selected research studies were conducted under field conditions and provided detailed records of fertilizer application, yield, and growth stages. After retrieval and screening, 11 datasets on wheat yield response to nitrogen fertilizer were compiled from these articles. The experimental sites selected for 2022-2023 included Tongshan District, Zhangjiagang County, Wuzhong County, and Xinghua County in Jiangsu Province, using both the FCN strategy and the N rates corresponding to attainable yield (Natt) strategy. At the maturity stage, plants from an area of 1 m² were harvested three times per plot for threshing and yield measurement. Irrigation, fertilizers, and pesticides were applied as needed to maintain optimal conditions for winter wheat growth, eliminating water and nutrient stress and controlling diseases and weeds.

Weather conditions significantly impact wheat growth. Daily climate data up to 2022 were obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn/), including daily maximum and minimum air temperatures, sunshine hours, and precipitation. After 2020, daily maximum and minimum temperatures and solar radiation were sourced from the ECMWF/ERA5_LAND/DAILY_AGGR dataset, which has a spatial resolution of 11,132 m. Rainfall data were obtained from the UCSB-CHG/CHIRPS/DAILY dataset, featuring a spatial resolution of 5 km.

Soil data used for model calibration and evaluation were matched with observed soil data from the nearest sites, based on the second national soil census dataset in China. These data included soil type, soil depth, number of layers, particle size structure, organic carbon content, pH, cation exchange capacity, total nitrogen concentration, and bulk density. The soil data were obtained from the Soil Science Data Center (http://soil.geodata.cn/) (Soil Sub Center, 2020).

Model calibration and evaluation

This study included three representative wheat cultivars: Huaimai20, Zhenmai12, and Yangmai23. These cultivars were used for both calibration and evaluation. Management practices, such as sowing date, sowing density, and water and nitrogen application, were recorded and used as model inputs. The genetic coefficients for all three cultivars were identical based on our calibration results.

The parameter calibration in this study involved two main steps: (1) Parameter Calibration. A trial-and-error method was employed to adjust the parameters of each cultivar. This process aimed to minimize the error between the simulated and observed growing stages and grain yield. Half of the data at each site were used for this calibration. (2) Parameter Validation. The remaining half of the data from the same region was used for validation. and grain yield were used for calibration and evaluation of the crop models. Crop phenology was calibrated first by adjusting parameters related to crop development. Subsequently, grain yield was calibrated by fine-tuning parameters that the models use to simulate grain yield (Table 1).

Table 1 Genetic coefficients of representative wheat cultivars in WheatGrow model

Cultivars	PVT	TS	PS	IE	FDF	HI	SLA	MAX
HM20	58.1	1.7	0.000756	0.956	0.948	0.38	0.0044	46
ZM12	13.3	1.4	0.000787	0.93	0.832	0.46	0.0023	35
YM23	58.1	1.03	0.00022	0.924	0.852	0.39	0.0026	35

Note: HM20-Huaimai20, ZM12-Zhenmai12, YM23-Yangmai23; PVT- Physiological vernalization time, TS- Temperature sensitivity; PS- Photoperiod sensitivity; IE- Intrinsic earliness; FDF- Filling duration factor; HI- Harvest index; MAX- Maximum photosynthetic rate.

The accuracy of the simulated growing stages and grain yield was assessed using the root mean square error (RMSE).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Oi - Si)}{N}} \qquad (1)$$

where O_i and S_i were the observed and simulated values, respectively; N was the total number of samples.

In-season optimum N rates

The economic optimal N rate (EONR) was defined as the minimum N fertilizer application rate to achieve the maximum marginal return based on the relationship between marginal return (MR) and N fertilizer application rates. n this study, the MR was calculated for each N rate using Equation 2. After calibration and validation, the model was used to estimate the in-season optimum N rate for winter wheat. The model incorporated in-season weather data from the beginning of the year to sowing (2022) and historical weather data from sowing to maturity (2016-2021). Model scenarios included nine N rates ranging from 0 to 400 kg N ha^{-1}, with increments of 50 kg N ha^{-1}. The predicted EONR values were compared with agronomic optimal N rate (AONR) to evaluate their accuracy. FCN strategy represents the local farmers' practices. N_{att} strategy was set up by the Ministry of Agriculture and Rural Development (MARD), with the attainable yield set as 7500 kg/ha. Specific descriptions of the trails are given in Table 2.

$$MR = Gy * Gp - Nr * Np \qquad (2)$$

where G_Y is the grain yield (kg ha^{-1}), G_P is the grain price (0.34 $ kg^{-1}), N_R is the N fertilizer rate (kg N ha^{-1}), and N_P is the N fertilizer price (0.79 $ kg^{-1}).

Table 2 Basic information about experimental design in 2022-2023

Sites	Cultivars	FCN (kg N ha^{-1})	N_{att} (kg N ha^{-1})	Sowing dates
Tongshan	HuaiMai20	360	211	2022/11/7
Zhangjiagang	ZhenMai12	300	211	2022/11/5
Xinghua	YangMai23	300	211	2022/11/6
Wuzhong	ZhenMai12	270	211	2022/11/5

Note: FCN- farmers conventional N rates; Natt- N rates corresponding to attainable yield.

To compare and evaluate the EONR strategy based on the WheatGrow model with FCN and Natt strategies, the wheat grain yield (kg ha^{-1}), marginal return ($ ha^{-1}), and N partial factor productivity (PFP, kg kg^{-1}) were calculated.

$$\text{PFP} = Y_N/N_R \qquad (3)$$

where YN is the grain yield (kg ha^{-1}) and NR is the N fertilizer application rate (kg ha^{-1}).

Results ans Dicussion

Model calibration and evaluation

Cultivar coefficients were estimated by fitting simulated and observed growing stages and grain yield using data collected from field experiments and published papers (Table 1). The model provided a good fit for both growing stages and grain yield (Fig. 1). The RMSE for growth stages was 3.1 days for Huaimai20, 10.2 days for Yangmai 23 and 8.8 days for Zhenmai12. For grain yield, the RMSE was 815 kg ha^{-1} for Huaimai20, 643 kg ha^{-1} for Yangmai23, and 1266 kg ha^{-1} for Zhenmai12. Subsequently, the model was evaluated using additional data, resulting in RMSE values of 4.0 days for Huaimai20, 10.0 days for Yangmai23, and 11.4 days for Zhenmai12 for growth stages, and 776.8 kg ha^{-1}, 793.3 kg ha^{-1}, and 1598 kg ha^{-1} for yield, respectively. The WheatGrow model's performance was consistent with previous studies (Ye et al., 2020), demonstrating its robustness in simulating wheat growth stages and yield. The reason for the poorer accuracy of Zhenmai 12 may be that the data were collected from published literature rather than field trails.

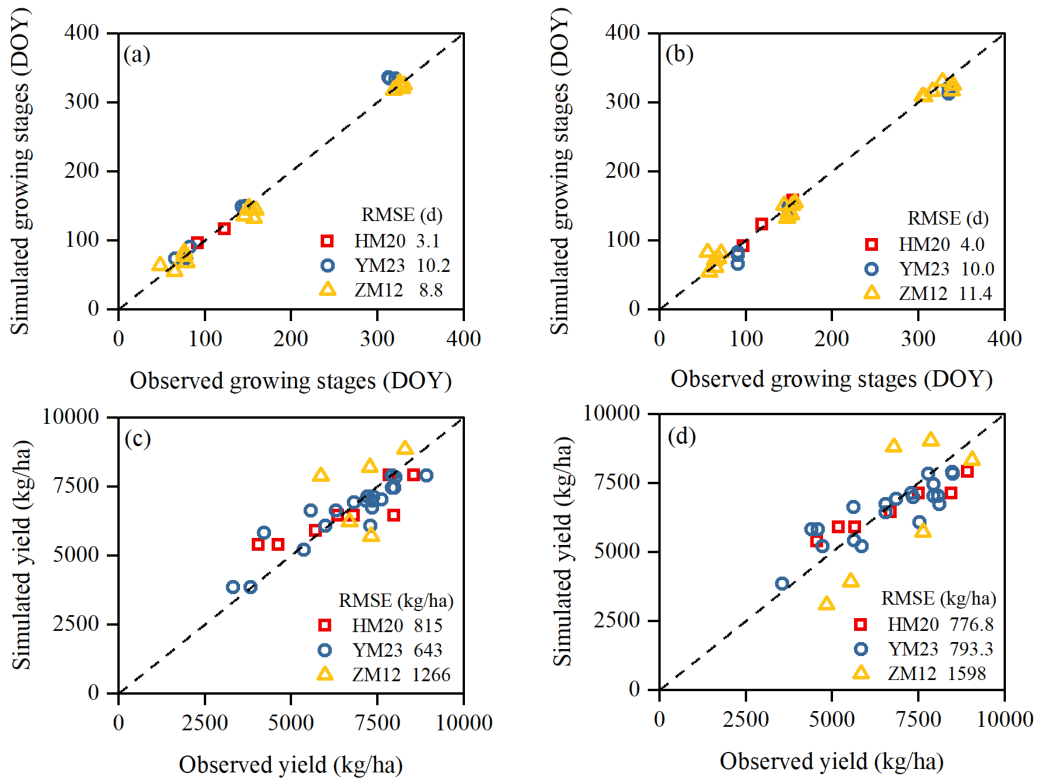

Fig 1. Comparison of simulated and observed growth stages (a, b) and grain yield (c, d) in model calibration (a, c) and evaluation (b, d). DOY: day of year.

In-season optimum N rates prediction

The calibrated model was employed to simulate wheat's EONR for 2022 using data from 2016 to 2021. Each site underwent five simulations using weather data from a different historical year from sowing to maturity. The simulated responses of marginal return to nitrogen (N) application rates are illustrated in Figure 2. It was observed that the marginal return in predicted EONR increased with N fertilizer rates. Across different sites, differences in simulated EONR were evident, with values of 230 kg ha^{-1} in Tongshan, 220 kg ha^{-1} in Xinghua, 210 kg ha^{-1} in Zhangjiagang, and 190 kg ha^{-1} in Wuzhong. Furthermore, the response of grain yield to N rates was examined to determine the ANOR, representing the minimum N rates to achieve the highest yield (Fig. 3). ANOR also exhibited considerable variations across locations, with values of 205 kg ha^{-1} in Tongshan, 219 kg ha^{-1} in Xinghua, 188 kg ha^{-1} in Zhangjiagang and 194 kg ha^{-1} in Wuzhong. Although the coefficient of determination (R^2) values (0.32) between ANOR and EONR were relatively low, the simulated in-season EONR values consistently fell within ± 20% of ANOR values (Fig. 4). Consequently, the optimal N rates recommended by the WheatGrow model can achieve the highest economic benefits while ensuring high yields.

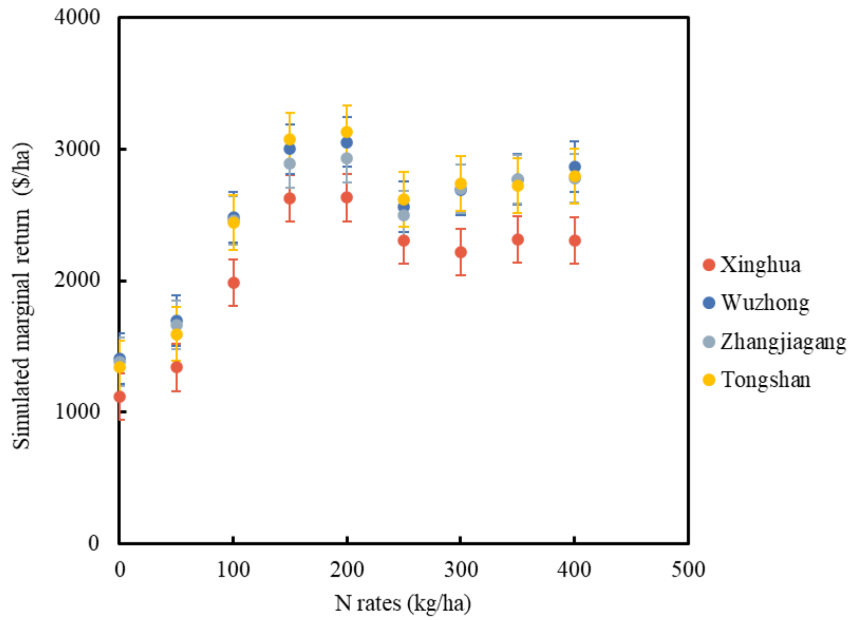

Fig 2. The response of simulated marginal return to N application rates at four sites. The bar is the standard deviation of simulated grain yield or marginal return across 5 years' historical weather data.

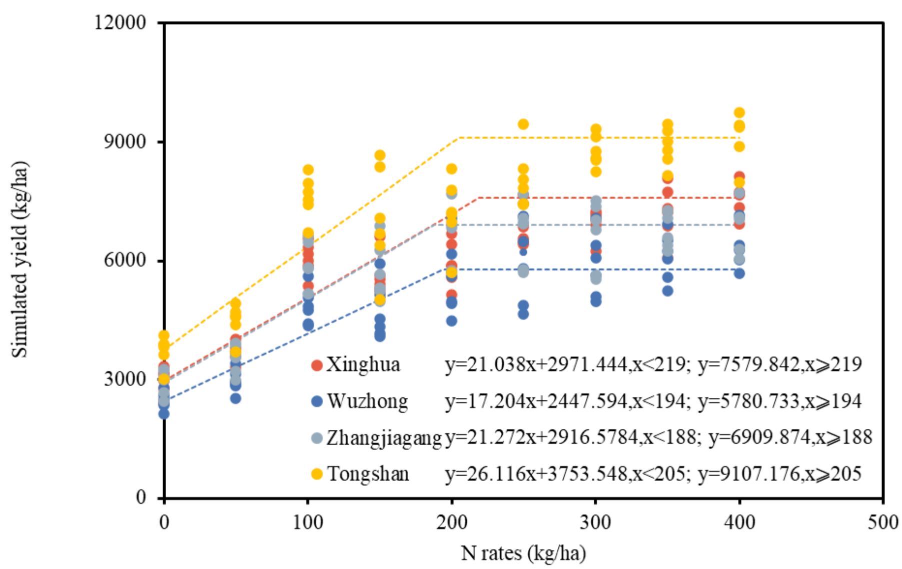

Fig 3. The response of simulated grain yield to N application rates at four sites.

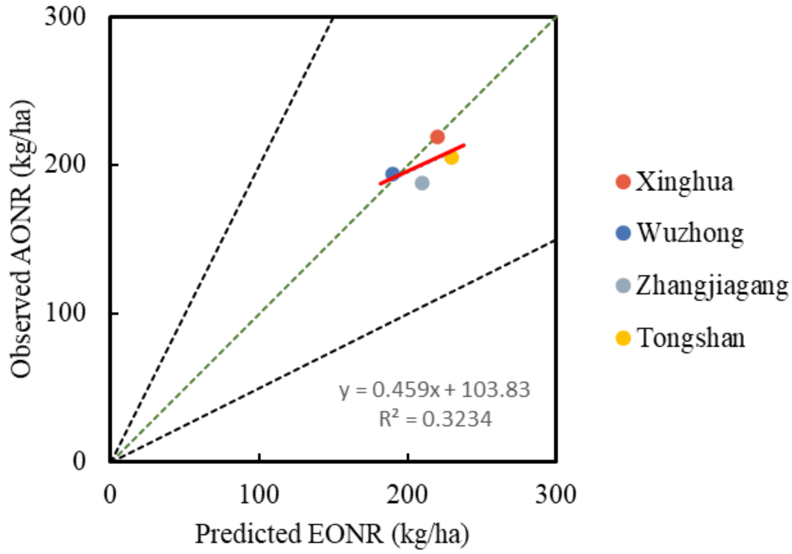

Fig 4. The relationships and differences between economical optimal N rate (EONR) and agronomic optimal N rate (AONR). (Note: the green dotted line represents 1:1 line; the black dotted lines represent 1:2 and 1:0.8 lines).

Evaluating in-season optimal N strategy

When comparing three different strategies, FCN, N_{att}, and EONR strategies, significant findings emerged (Table 3). The EONR strategy demonstrated great potential to reduce N rates by 30% and improve PFP by 34% in Zhangjiagang, and 36% in N rates and 51% in PFP for Tongshan. could reduce N rates by 30% and improve PFP by 34% for Zhangjiagang, 30% N rates and 33% PFP for Wuzhong, 30% N rates and 34% PFP for Xinghua, and 36% N rates and 51% PFP for Tongshan. Notably, the EONR strategy consistently yielded similar crop yields and economic benefits compared to the FCN strategy. There is no significant differences between the EONR and Natt strategies, except in the case of the Tongshan district.

Table 3 The difference in yield, partial factor productivity (PFP) and economic benefits among farmers conventional N rates (FCN), N rates corresponding to attainable yield (N_{att}) and EONR strategies.

three different nitrogen fertilizer management strategies

	Strategies	Yield (kg/ha)	PFP (kg/kg)	Economic benefits ($/ha)
Tongshan	FCN	9466a	26.3c	2934.0a
	N_{att}	9800a	46.4a	3165.3a
	EONR	9107a	39.6b	2914.7a
Xinghua	FCN	7739a	25.8b	2394.3a
	N_{att}	7628a	36.2a	2426.8a
	EONR	7580a	34.5a	2411.3a
Wuzhong	FCN	6125a	22.7b	1869.2a
	N_{att}	5994a	28.4a	1871.3a
	EONR	5716a	30.1a	1793.3a
Zhangjiagang	FCN	7200a	24.5b	2188.6a
	N_{att}	6829a	32.4a	2155.2a
	EONR	6910a	32.9a	2183.5a

Conclusion

The findings of this study underscore the considerable potential of the WheatGrow model in accurately simulating wheat growth stages (RMSE= 3.1-11.4 days) and grain yield (RMSE= 643-1598 kg/ha). By integrating both current and historical weather data, the Economic Optimum Nitrogen Rate (EONR) recommendations generated by the WheatGrow model consistently fell within ± 20% of the agronomic optimal N rates (AONR). Specifically, optimal N rates were determined to be 220 kg ha^{-1} for Xinghua, 190 kg ha^{-1} for Wuzhong, 210 kg ha^{-1} for Zhangjiagang, and 230 kg ha^{-1} for Tongshan, respectively. Compared with farmers conventional N rates (FCN) and N rates corresponding to attainable yield (Natt), EONR strategy based on crop model could improve PFP by 33-51% while maintaining simultaneously yield and economic benefits. In conclusion, the WheatGrow model could be viewed as a valuable tool for simulating the wheat growing stages and yield and optimizing N management. The methodology in this study lays the groundwork for potential integration with in-season sensing data to further enhance precision N management strategies.

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